Edinburgh 2003/13, MPP-2003-49, PSI-PR-03-14

Higgs Radiation off Bottom Quarks at the Tevatron and the LHC

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Abstract

Higgs-boson production in association with bottom quarks, $p\bar{p}/pp \to b\bar{b}H + X$, is one of the most important discovery channels for supersymmetric Higgs particles at the Tevatron and the LHC. We have calculated the next-to-leading order QCD corrections to the parton processes $q\bar{q}, gg \to b\bar{b}H$ and present results for total cross sections and for distributions in the transverse momenta of the bottom quarks. The QCD corrections reduce the renormalization and factorization scale dependence and thus stabilize the theoretical predictions, especially when the Higgs boson is produced in association with high-p_T bottom quarks. The next-to-leading order predictions for the total cross section are in reasonable numerical agreement with calculations based on bottom-quark fusion $b\bar{b} \to H$.

The Higgs mechanism [1] is a cornerstone of the Standard Model (SM) and its supersymmetric extensions. The masses of the fundamental particles, electroweak gauge bosons, leptons, and quarks, are generated by interactions with Higgs fields. The search for Higgs bosons is thus one of the most important endeavours in high-energy physics and is being pursued at the upgraded proton–antiproton collider Tevatron [2] with a centre-of-mass (CM) energy of 1.96 TeV, followed in the near future by the proton–proton collider LHC [3] with 14 TeV CM energy.

Various channels can be exploited to search for Higgs bosons at hadron colliders. Higgs radiation off bottom quarks [4]

$$p\bar{p}/pp \to b\bar{b}H \ + \ X \qquad \text{via} \qquad q\bar{q}, gg \to b\bar{b}H \tag{1}$$

is the dominant Higgs-boson production mechanism in supersymmetric theories at large $\tan\beta$, where the bottom–Higgs Yukawa coupling is strongly enhanced. The parameter $\tan\beta = v_2/v_1$ is the ratio of the vacuum expectation values of the two Higgs fields generating the masses of up- and down-type particles in supersymmetric extensions of the SM. $H = H_{\mathrm{SM}}, h^0, H^0$ may denote the SM Higgs boson or any of the CP-even neutral Higgs bosons of supersymmetric theories. In the SM the Yukawa coupling strength is given by $g_{ffH,\mathrm{SM}} = m_f/v$, where m_f denotes the mass of fermion f and $v \approx 246$ GeV is the vacuum expectation value of the SM Higgs field. In the minimal supersymmetric extension of the SM (MSSM) the Yukawa couplings are modified by the factors $\hat{g}_{ffH} = g_{ffH,\mathrm{MSSM}}/g_{ffH,\mathrm{SM}}$,

$$\hat{g}_{uuh^0} = \frac{\cos\alpha}{\sin\beta}, \quad \hat{g}_{uuH^0} = \frac{\sin\alpha}{\sin\beta}, \quad \hat{g}_{ddh^0} = -\frac{\sin\alpha}{\cos\beta}, \quad \hat{g}_{ddH^0} = \frac{\cos\alpha}{\cos\beta}, \tag{2}$$

where $v = \sqrt{v_1^2 + v_2^2}$ and α is the mixing angle of the CP-even Higgs fields h^0 and H^0 [5].

Leading-order (LO) predictions for the cross sections (1) are plagued by considerable uncertainties due to the strong dependence on the renormalization and factorization scales, introduced by the QCD coupling, the parton densities, and the running b-quark mass in the bottom–Higgs Yukawa coupling. In this letter we present the first calculation of the next-to-leading order (NLO) QCD corrections to associated $b\bar{b}H$ production at hadron colliders through the parton processes $q\bar{q}, gg \to b\bar{b}H$.

Note that the inclusive cross-section prediction for the process $gg \to b\bar{b}H$ develops potentially large logarithmic terms $\propto \ln(m_b/Q)$. The logarithms arise from the splitting of gluons into $b\bar{b}$ pairs where the b-quark mass acts as a cutoff for the collinear singularity. The large scale Q corresponds to the upper limit of the collinear region up to which factorization is valid. It has been argued that Q is of the order $M_H/4$ or less [6]. The $\ln(m_b/Q)$ terms can be summed to all orders in perturbation theory by introducing bottom parton densities [7], provided that the b-quarks are produced predominantly at small transverse momentum. In this approach [8, 9, 10], the counting of perturbative orders involves both the strong coupling α_{s} and the logarithm $\ln(m_b/Q)$. The LO process is Higgs-boson production through $b\bar{b}$ fusion, $b\bar{b} \to H$. The first order corrections comprise the $\mathcal{O}(\alpha_{\mathrm{s}})$ corrections to $b\bar{b} \to H$ and the LO process $gb \to bH$, which is suppressed with respect to $b\bar{b} \to H$ by $1/\ln(m_b/Q)$. The second-order corrections, involving $b\bar{b} \to H$ at NNLO, have been completed recently [10] and strongly reduce the spurious scale dependence of the total cross-section prediction.

Higgs searches in the $b\bar{b}H$ channel, however, do in general employ cuts on the b-quark transverse momenta and thus require theoretical predictions for exclusive final states. This problem cannot be solved within the b-quark density approach, since per definition the

transverse momenta of spectator b-quarks are integrated out. The solution in this case is provided by calculations based on the parton processes $q\bar{q}, gg \to b\bar{b}H$. In this letter we present NLO results for both inclusive and exclusive observables, based on these parton processes. We also include a first numerical comparison of our results with calculations based on the $b\bar{b}$ fusion process.

Generic diagrams that contribute to the processes (1) at LO are displayed in Fig. 1(a). The NLO corrections comprise virtual one-loop diagrams, Fig. 1(b), gluon radiation processes, Fig. 1(c), and gluon-(anti)quark scattering reactions, Fig. 1(d). The latter two add incoherently to the virtual corrections. The calculation of the NLO QCD corrections to the processes $q\bar{q}, gg \to Q\overline{Q}H$, where Q denotes a generic heavy quark, has been described in detail in Ref. [11] (see also Ref. [12]). In the following we define the physical input parameters and quote their values as chosen for the numerical analysis. The renormalization of the strong coupling $\alpha_s(\mu)$ and the factorization of initial-state collinear singularities are performed in the $\overline{\mathrm{MS}}$ scheme. For the calculation of the pp and $p\bar{p}$ cross sections we have adopted the CTEQ6L1 and CTEQ6M [13] parton distribution functions at LO and NLO, corresponding to $\Lambda_5^{\mathrm{LO}} = 165$ MeV and $\Lambda_5^{\overline{\mathrm{MS}}} = 226$ MeV at the one- and two-loop level of the strong coupling $\alpha_s(\mu)$, respectively.[1] The top quark is decoupled from the running of $\alpha_s(\mu)$. We evaluate the bottom–Higgs Yukawa coupling with the running b-quark mass $\overline{m}_b(\mu)$ defined in the $\overline{\mathrm{MS}}$ scheme in order to sum large logarithmic corrections $\propto \ln(m_b/M_H)$ related to the renormalization of the Yukawa coupling [14]. The b-quark pole mass has been set to $m_b = 4.62$ GeV, corresponding to a $\overline{\mathrm{MS}}$ mass $\overline{m}_b(\overline{m}_b) = 4.28$ GeV [15]. The strength of the SM Yukawa coupling is fixed by $g_{bbH} = \overline{m}_b(\mu)/v$, where $v = (\sqrt{2}G_F)^{-1/2}$ is the vacuum expectation value of the Higgs field and $G_F = 1.16639 \times 10^{-5}$ GeV^{-2}.

In the following we present the NLO QCD predictions for associated $b\bar{b}H$ production at the Tevatron and the LHC in the SM. In LO, the transition to the MSSM can be done by a simple rescaling of cross sections and distributions with a factor $\hat{g}^2_{bbh^0/bbH^0}$, since the LO matrix element is proportional to the bottom-quark Yukawa coupling g_{bbh^0/bbH^0}. In NLO, this rescaling is spoiled by one-loop diagrams in which the Higgs boson couples to a closed top-quark loop (the corresponding quark loops of the first two generations are negligible). However, our calculation reveals that these contributions only amount to about $-5\%(-10\%)$ of the NLO cross section at the Tevatron (LHC) in the SM. Thus, to a very good approximation, also the cross sections and distributions including NLO QCD corrections follow the simple LO rescaling. We do not consider supersymmetric-QCD and electroweak corrections in this paper.[2] For a consistent comparison of LO and NLO results, all quantities (α_s, the parton densities, the running b-quark mass, and the partonic cross sections) are calculated in LO and NLO, respectively. We first discuss the renormalization and factorization scale dependence. All scales (including the scale of the running b-quark mass) have been set equal, $\mu = \mu_F = \mu_R$, and are varied around the central value $\mu_0 = (2m_b + M_H)/2$. Figures 2 and 3 show the scale dependence for both the total cross section and the cross section with two

[1] The CTEQ6 parton distribution functions involve five active quark flavours. In our calculation we do not include b quarks as active partons. The gluon distribution is enhanced in a scheme with four active flavours, but the effect is numerically small, less than 5%, and has been neglected in the present analysis.

[2] For large $\tan\beta$, supersymmetric loop corrections to the $b\bar{b}h^0/H^0$ vertices may become important [16]. In the present QCD analysis, the major part of these corrections can be absorbed into effective Higgs Yukawa couplings, since emission and reabsorption of virtual heavy supersymmetric particles is confined to small space-time regions compared with QCD subprocesses involving massless gluons.

TABLE I: Total cross sections for $q\bar{q}, gg \to b\bar{b}H + X$ and $b\bar{b} \to H + X$ [10] at the Tevatron and the LHC. In the $q\bar{q}, gg \to b\bar{b}H + X$ calculation the renormalization and factorization scales have been set equal to $\mu = \mu_0/2 = (2m_b + M_H)/4$ and are varied between $\mu = \mu_0/4$ (upper limit) and $\mu = \mu_0$ (lower limit). In the calculation based on the $b\bar{b} \to H + X$ process the renormalization scale has been fixed to $\mu_R = M_H$, while the factorization scale is varied between $0.1M_H \leq \mu_F \leq 0.7M_H$ with $\mu_F = 0.25M_H$ as the central scale. Note that the $b\bar{b} \to H + X$ calculation employs MRST LO and NNLO parton distribution functions [17].

	M_H [GeV]	$\sigma(q\bar{q}, gg \to b\bar{b}H + X)$ [fb]		$\sigma(b\bar{b} \to H + X)$ [fb]	
		LO	NLO	LO	NNLO
Tevatron	120	$3.9^{+3.5}_{-1.7}$	$6.5^{+1.5}_{-1.7}$	$8.6^{+4.7}_{-5.0}$	$10.5^{+0.3}_{-1.1}$
	200	$0.22^{+0.19}_{-0.09}$	$0.49^{+0.15}_{-0.15}$	$0.69^{+0.20}_{-0.26}$	$0.79^{+0.02}_{-0.03}$
LHC	120	$(5.3^{+2.7}_{-1.7}) \times 10^2$	$(5.8^{+1.0}_{-1.0}) \times 10^2$	$(4.8^{+4.3}_{-3.2}) \times 10^2$	$(7.2^{+0.4}_{-1.6}) \times 10^2$
	400	$4.3^{+2.4}_{-1.4}$	$7.2^{+1.7}_{-1.5}$	$7.4^{+2.4}_{-2.5}$	$9.8^{+0.2}_{-0.4}$

high-p_T bottom quarks. The reduction of the spurious scale dependence at NLO is particularly striking for the exclusive cross section where both b-quarks are required to be produced with $p_T > 20$ GeV. A significant reduction of the scale dependence is also observed when demanding only one of the b-quarks to be produced at large p_T (not shown). The residual scale dependence of the inclusive cross section is still sizeable at NLO, and further work is needed to improve the theoretical prediction. Note that large logarithmic corrections may spoil the convergence of perturbation theory if μ is chosen too low. This is evident from the exclusive cross section at the Tevatron, Fig. 2, where the NLO prediction would even turn negative for $\mu \lesssim \mu_0/5$. A similar observation has been made for $t\bar{t}H$ production at the Tevatron [11]. We note that the $b\bar{b}H$ cross section at the Tevatron and the LHC is completely dominated by the gluon-gluon fusion and gluon-(anti)quark scattering reactions.

The total cross section for associated $b\bar{b}H$ production at the Tevatron and the LHC is displayed in Fig. 4 as a function of the Higgs-boson mass. We have set all scales equal to $\mu = \mu_0/2 = (2m_b + M_H)/4$, which is a suitable factorization scale choice for calculations based on the $b\bar{b}$ fusion process [8, 9, 10]. For this choice of scales, the NLO QCD corrections increase the theoretical prediction significantly, by a factor $1.6 - 2.3$ at the Tevatron and $1.1 - 1.8$ at the LHC. Representative results for the total cross section are listed in Table I and are compared with the NNLO calculation based on b-quark fusion $b\bar{b} \to H$ [10]. When including higher-order QCD corrections, the results obtained in the two approaches are in reasonable numerical agreement.[3] In particular, the cross-section predictions for $b\bar{b}H$ production at the LHC are compatible within their respective scale uncertainties. We would like to emphasize, however, that in spite of the qualitative numerical agreement between the $q\bar{q}, gg \to b\bar{b}H$ and $b\bar{b} \to H$ cross-section predictions, the intrinsic uncertainties of both

[3] Note that contributions involving Higgs radiation off a closed top-quark loop have not been included in the b-quark fusion calculation [10]. While these contributions are negligible in supersymmetric theories at large $\tan\beta$, they do affect the SM cross section. Higgs radiation of top-quark loops has been included in the calculation presented in this letter and reduces the cross-section prediction in the SM by $5 - 10\%$.

approaches have not yet been fully quantified.

In Figures 5 and 6 we show the cross section with one or two high-p_T bottom quarks as a function of the minimal b-quark transverse momentum. We observe sizeable positive corrections if the b-quarks are produced at small p_T. If both b-quarks are required to be produced with larger $p_T \gtrsim 20$ GeV the NLO corrections reduce the LO prediction. The cross-section predictions with a single high-p_T bottom quark will be compared with calculations based on the parton process $gb \to bH$ [9] in a forthcoming publication.

In summary, the strong scale dependence of the LO predictions for the processes $p\bar{p}/pp \to b\bar{b}H+X$, which provide important search channels for supersymmetric Higgs bosons, requires the inclusion of QCD corrections. For the total cross section, we find a reduction of the spurious scale dependence at NLO, but further improvements are needed to quantify the accuracy of the prediction. Still, our results are in reasonable numerical agreement with calculations based on the bottom-quark fusion process. We find a drastic reduction of the scale dependence at NLO when the Higgs boson is produced in association with high-p_T bottom quarks. The improved NLO predictions for the exclusive cross sections can thus be taken as a base for experimental analyses at the Tevatron and the LHC.

Note added in proof

After submission of this paper, an independent calculation of the exclusive $b\bar{b}H$ cross section with two high-p_T b-quarks has been presented in Ref. [18]. The authors of Ref. [18] have chosen a different set of input parameters and final-state cuts, so that a direct comparison with the results presented in our paper is not possible. A systematic comparison of the two calculations is, however, now in progress, and good agreement has been found for the exclusive $b\bar{b}H$ cross section with high-p_T b-quarks, see Ref. [19]. Ref. [19] also includes a comparison of the cross-section predictions with calculations based on the parton process $gb \to bH$.

Acknowledgments

The authors are pleased to thank W. Beenakker, B. Plümper and P.M. Zerwas for their collaboration on Ref. [11], and W. Beenakker and P.M. Zerwas for comments on the manuscript. We are grateful to the authors of Ref. [18] for a comparison of results, and to R. Harlander for providing us with the results of the calculation Ref. [10]. We also thank S. Dawson, F. Maltoni, T. Plehn, L. Reina and S. Willenbrock for discussions. This work has been supported by the European Union under contract HPRN-CT-2000-00149.

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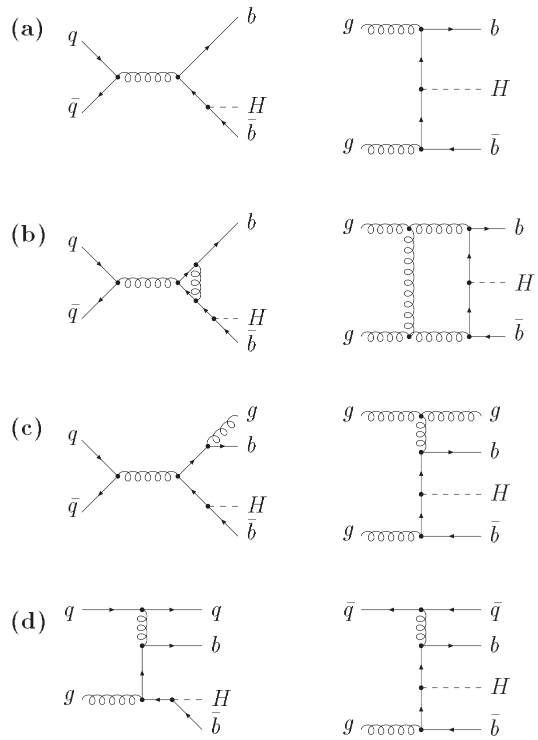

FIG. 1: A generic set of diagrams (a) for the Born level, (b) for virtual gluon exchange, (c) gluon radiation and (d) gluon-(anti)quark scattering in the subprocesses $q\bar{q}, gg \to b\bar{b}H$ etc.

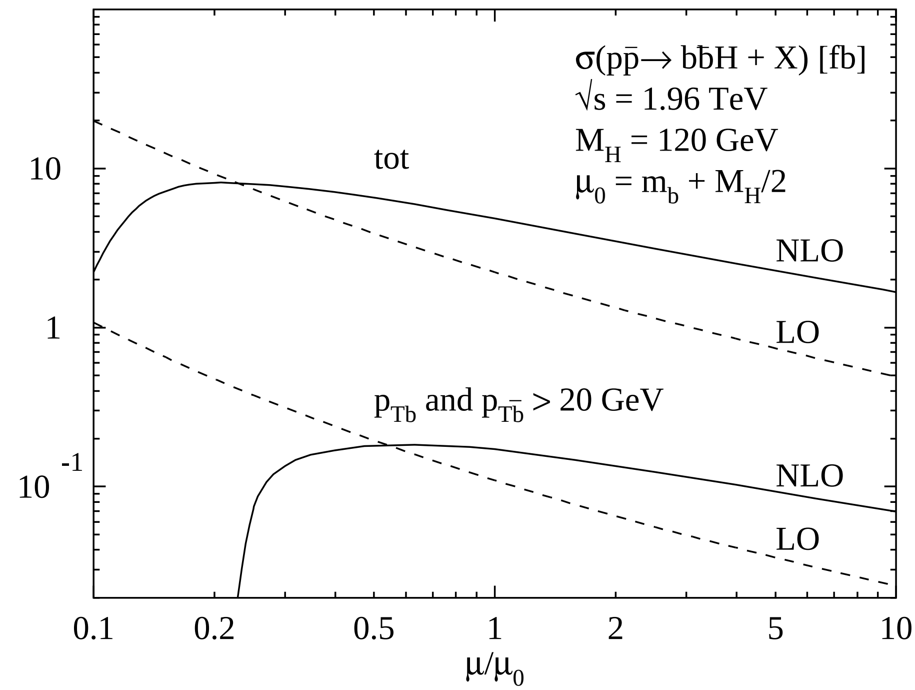

FIG. 2: Variation of the LO and NLO cross sections with the renormalization and factorization scales for $p\bar{p} \to b\bar{b}H + X$ at the Tevatron.

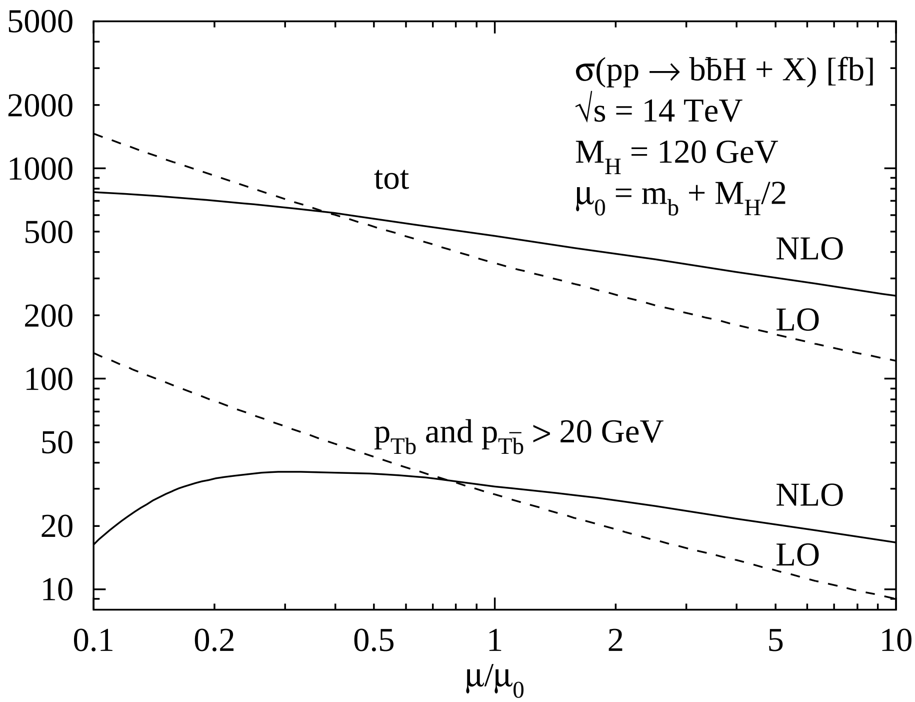

FIG. 3: Variation of the LO and NLO cross sections with the renormalization and factorization scales for $pp \to b\bar{b}H + X$ at the LHC.

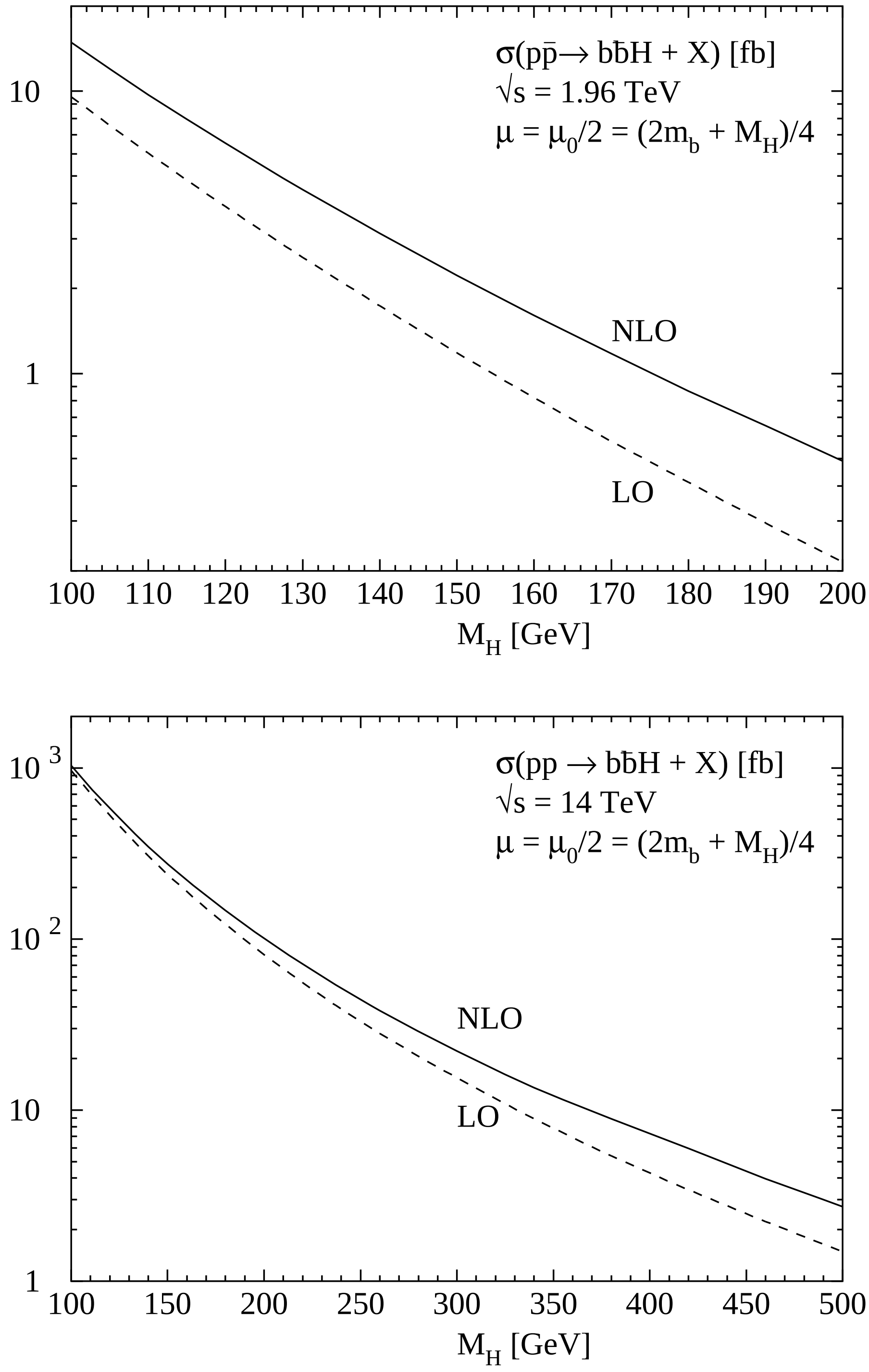

FIG. 4: Total cross section for $p\bar{p} \to b\bar{b}H + X$ at the Tevatron (upper figure) and $pp \to b\bar{b}H + X$ at the LHC (lower figure) as a function of the Higgs boson mass.

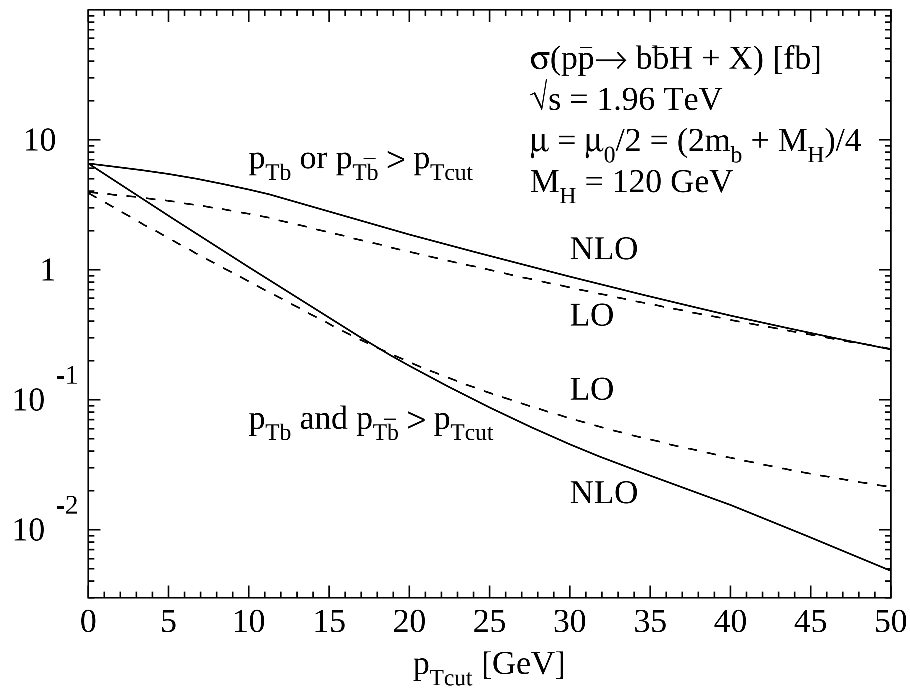

FIG. 5: Cross section for $p\bar{p} \to b\bar{b}H + X$ at the Tevatron with one or two high-p_T bottom quarks as a function of the minimal b-quark transverse momentum.

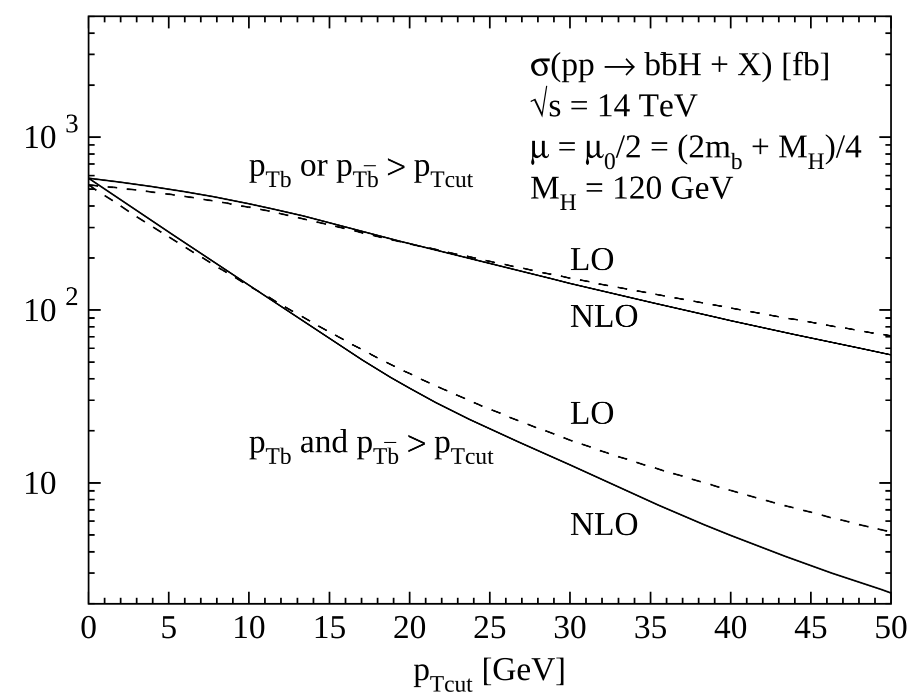

FIG. 6: Cross section for $pp \to b\bar{b}H + X$ at the LHC with one or two high-p_T bottom quarks as a function of the minimal b-quark transverse momentum.